SPACE DEBRIS RESEARCH IN THE U.S. DEPARTMENT OF DEFENSE

David B. Spencer
USAF Phillips Laboratory, (PL/VTS) 3550 Aberdeen Ave. SE, Kirtland AFB, NM 87117-5776 USA

W. Spencer Campbell
The Aerospace Corporation, P.O. Box 9045, Albuquerque, NM 87119-9045 USA

Abstract

A research program was established by the United States Department of Defense (DoD) at the U.S. Air Force's Phillips Laboratory (PL) in 1990 to assess the small orbital debris environment, characterize the hazard it might pose to DoD assets, and develop new mitigation techniques to minimize the creation of debris. This program is comprised of three areas of activity: *debris measurements, debris modeling, and debris mitigation*. Debris measurements are utilized to understand the current environment and to observe growth trends. Debris modeling allows for estimates of the unmeasured population and its possible effects on space operations. Debris mitigation studies are conducted to develop strategies for debris minimization and protection. The purpose of this paper is to present an overview of the space debris research and analysis capabilities that exist in the U.S. Department of Defense.

1. INTRODUCTION

Space debris is defined in this paper as any non-functioning man-made object orbiting the Earth. This definition distinguishes space debris from functioning operational payloads and natural meteoroids which orbit the Earth or pass through the Earth's orbit. The key question raised by the space debris problem is *what is the likelihood that a given space asset will be damaged from a collision with another object?* This question needs to be addressed for both current and possible future debris populations. As more objects orbit the Earth, the probability for collision increases. Space debris would not be a potential problem if space assets could avoid or withstand a collision. However, avoiding collisions would require precise ground tracking and space vehicle maneuvering capabilities, and withstanding impacts can be prohibitively expensive. The level of damage a piece of debris can do depends on debris size, impact velocity, and spacecraft design specifics such as component positioning and materials. In the worst case, an impact with a large piece of debris could destroy a space asset, potentially increasing the space debris population and thereby increasing the hazard to other systems. For an average sized DoD satellite in LEO, the chance of a large piece of debris colliding with the asset is on the order of one in a thousand years. Less dramatic is damage from smaller debris which can result in pitting and surface erosion.

DoD Program History: The DoD space debris research program was established as a result of policy statements made in the late 1980's[1,2]. The U.S. Air Force (USAF) was tasked as the lead DoD service and the USAF Space Technology Center (now the Phillips Laboratory) was made the technical lead. NASA's technical lead is the Johnson Space Center. To carry out the 1989 U.S. Interagency Group IG(Space) report[3] recommendations on orbital debris, a DoD/NASA study was conducted. That study provided more detailed goals for the research program and recommended that it consist of two phases. In the first phase, emphasis was placed on increasing knowledge of the debris environment in LEO. The second phase focused on determining the debris hazard and on improving spacecraft survivability. A program plan was submitted to the National Space Council and approved in July 1990. The DoD and NASA phase one programs were completed in December 1993[4].

The National Research Council[5], at the request of NASA, formed a committee to draw upon available space debris data and analyses to:

- Characterize the current debris environment;
- Project how this environment might change without any new debris mitigation processes;
- Examine mitigation practices;
- Explore new ways to address the problem; and
- Develop recommendations on technical methods to address the problems of debris proliferation.

The NRC released their report in 1995.

Also in 1995, the White House Office of Science and Technology Policy (OSTP) released a report on space debris that gave several recommendations on areas of space debris research and analysis[6]:

- Continue and enhance debris measurement, modeling and monitoring capabilities;
- Conduct a focused study on debris and emerging LEO systems;
- Develop government/industry design guidelines on orbital debris;
- Develop a strategy for international discussions;
- Review and update U.S. policy on debris.

NASA and the Department of Defense, along with other U.S. government departments and agencies are currently working to develop a plan addressing the recommendations of both the NRC and OSTP reports.

On September 14, 1996, President Clinton signed the latest National Space Policy[7]. The policy states that "The United States will seek to minimize the creation of space debris. NASA, the Intelligence Community, and the DoD, in cooperation with the private sector, will develop design guidelines for future government procurements of spacecraft, launch vehicles, and services. The design and operation of space tests, experiments and systems, will minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness. It is in the interest of the U.S. Government to ensure that space debris minimization practices are applied by other spacefaring nations and international organizations. The U.S. Government will take a leadership role in international fora to adopt policies and practices aimed at debris minimization and will cooperate internationally in the exchange of information on debris research and the identification of debris mitigation options." The policy is consistent with the goals of the Interagency Space Debris Coordination Committee (IADC), the United Nations' Committee on the Peaceful Uses of Outer Space (UNCOPUOS), and other inter-governmental working groups.

2. CURRENT ACTIVITIES

Figure 1 shows the program organization and the relationships with other military organizations. Further information on the details of this organization can be found in reference 8. The technical approach employed by the DoD program is to focus research efforts in the areas of debris measurements, debris modeling, and debris mitigation. Measurement efforts are geared toward advancing measurement capabilities in detecting and tracking small objects not currently in the U.S. Space Command catalog. Modeling activities involve estimating current and projected environments, comparing results with measurement data, and modeling the effects of space debris on space

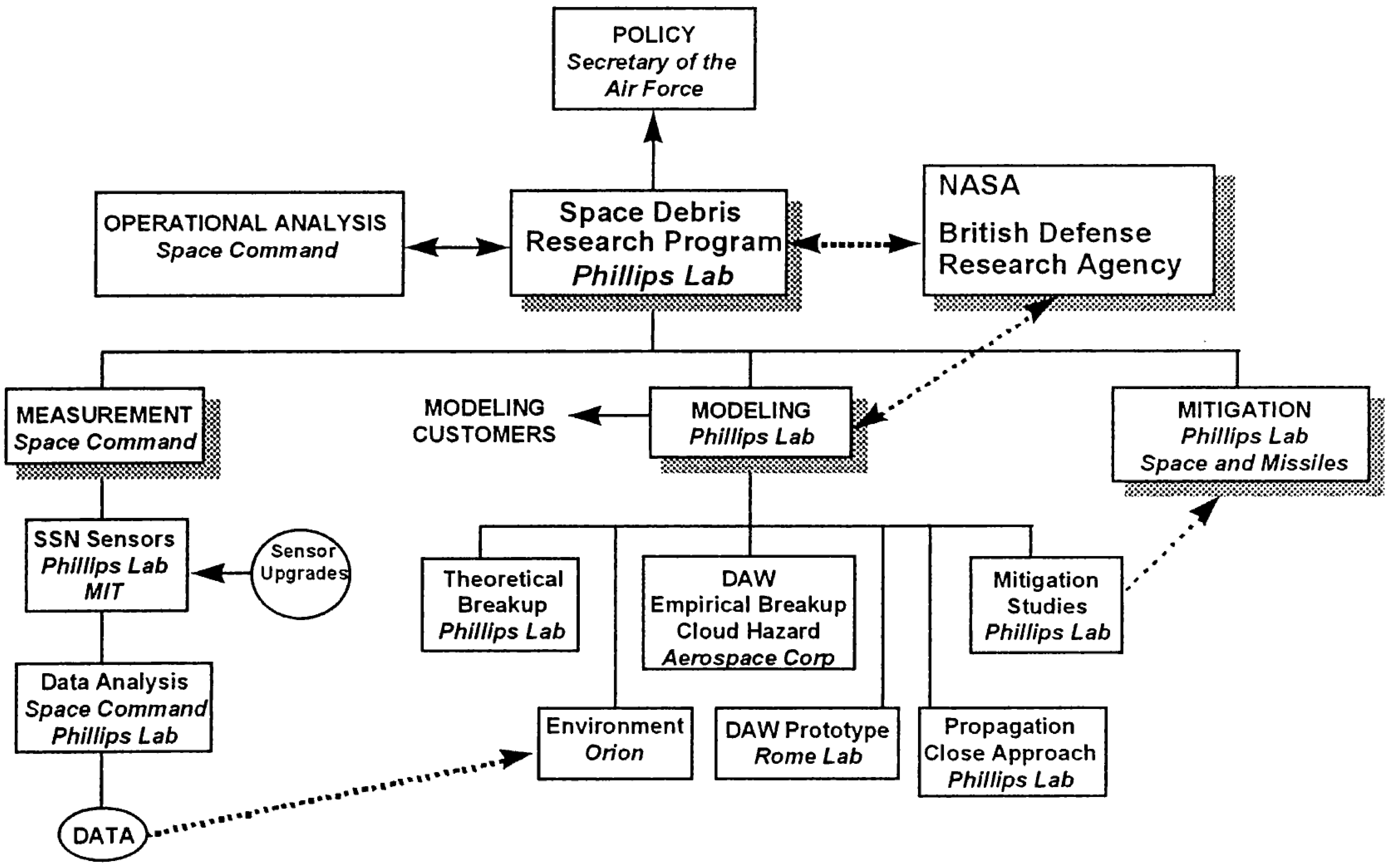


Figure 1 Space Debris Research Program Organization

operations. Mitigation activities involve using measurement results and modeling tools to recommend cost-effective strategies in support of the DoD and National Space Policies to limit superfluous debris.

Debris Measurements: Phase two DoD measurement activities are currently comprised of periodic measurement campaigns. The first campaign was conducted during the phase one program in June 1993 and the second was completed in October 1994. The purpose of these campaigns is to employ Space Surveillance Network (SSN) sensors and other cooperating sensors to detect, track, identify, and maintain tracks for uncataloged space debris.

Debris Modeling: Several models must be used together to quantify the potential hazards that are associated with space debris. These hazards result from operating spacecraft within a background debris population, and from operations near recent breakups. There are also hazards associated with sub-orbital debris or reentering debris. Given a breakup event, several tools can be used estimate the collision hazards.

MAGI is a theoretical model that is used to assess the material degradation, cratering, perforation, and fragmentation damage from debris impacts to specific space structures. It is a smoothed particle hydrodynamics (SPH) based simulation tool that was developed at PL.

IMPACT[9] is a semi-empirical model that is used to simulate and analyze the fragmentation of vehicles due to explosions and hypervelocity collisions. It uses a semi-empirical method in which the algorithms are based on data from breakup tests and on-orbit fragmentations. The program also imposes physical conservation laws of mass, energy, and momentum. IMPACT also interfaces with program FOOTPRINT to determine terrestrial re-entry positions of sub-orbital fragments.

The DEBRIS[10] model uses fragmentation data from IMPACT to simulate orbital debris cloud motion and determine the short-term collision hazard posed to a satellite operating near a recently formed debris cloud.

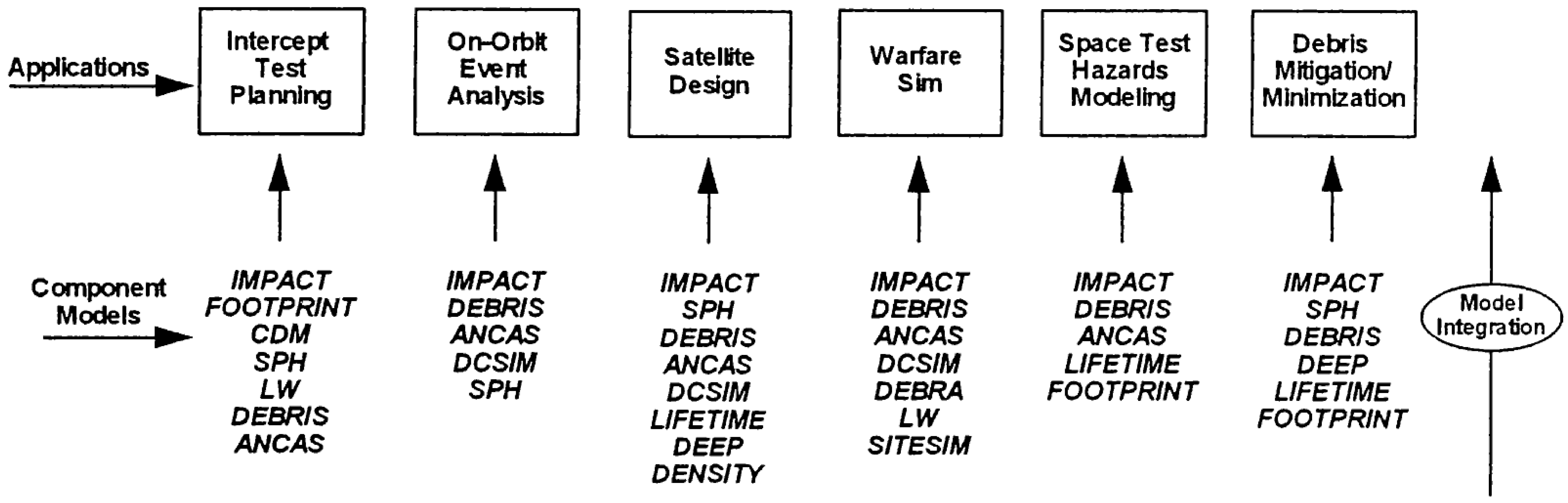
A detailed understanding of the hazards associated with debris producing events is much easier if the propagating debris cloud and space asset orbit can be graphically displayed and animated. A model called DCSIM (Debris Cloud SIMulator)[11] does this by displaying and animating the output from the IMPACT and DEBRIS models.

A model called ANCAS[12] was developed to quantify collision hazards deterministically (as opposed to probabilistically), and determine close approaches in time and distance between a particular space object and a population of Earth orbiting objects.

Objects and fragments can re-enter the Earth's atmosphere because of the atmospheric drag forces present at lower altitudes. The LIFETIME[13] program is used to determine the orbital lifetime of satellites and fragments. It simulates orbital evolution due to perturbations such as solar effects on the Earth's atmosphere and geomagnetic field. The algorithm used is based on semi-analytical orbital averaging to propagate objects quickly to re-entry. LIFETIME has a direct interface with the IMPACT breakup model.

DENSITY[14] is a model that determines spatial distributions of known orbital objects including satellites, upper-stages and debris by statistically representing the object orbits. It is used to determine the contribution by measured object orbits (satellites, upper-stages, and breakup fragments) and planned orbits (e.g. a satellite constellation) to the background population. DENSITY has been used to statistically estimate collision hazards for operations through proposed satellite constellations.

The phase one program identified several applications that can use the aforementioned debris models to assess various debris hazards. An effort was initiated to integrate component models to simplify and expedite the analysis process. The product is called the Debris Analysis Workstation (DAW)[15]. It is a SUN Workstation based suite of software tools that support a wide variety of debris related analyses for DoD customers. Figure 2 shows these applications and the component models that may be used collectively in order to conduct the analysis for each application.



Debris Hazard Assessment Models

IMPACT = semi-empirical breakup model
DEBRIS = short term debris cloud propagator and hazard model
LIFETIME = orbital lifetime model
LW = launch window model
CDM = collision dispersion model
DENSITY = spatial density model
DEEP = debris environment and effects program
DCSIM = debris cloud simulation tool
ANCAS = close approach model
DEBRA = debris radiance model (end to end simulation)
SPH = theoretical breakup model

Figure 2 DAW Applications and Component Models

Debris Mitigation: The Phillips Laboratory began applying its debris modeling tools for debris mitigation studies in 1994. The initial effort was a debris assessment for a commercial low Earth orbit (LEO) communications constellation project in the conceptual phase. The project had identified debris mitigation as a top-level system design requirement to allow the operational orbit to be maintained with minimum debris risk for future generations of project systems and other space users. The project's debris policy was considered to be evolutionary with its review a continuing activity for design support; this would feature update of preliminary studies with design revisions as well as analyses for re-entry burn-up and debris footprint determinations. Project goals were well aligned with the intent of NASA guidelines so a portion of the PL assessment was devoted to determining project compliance to those guidelines. This was to be considered a preliminary debris study since the spacecraft design was only conceptual, but the study also had an objective to identify follow-on tasks for support to the design phase. Design-specific analysis is needed for determining lethality of debris, response to impacts, and more formal compliance with space debris guidelines.

It was found that the project's debris policy incorporated National space policy, NASA and Air Force guidelines; further, the system requirements supported the debris policy with the exception of analyzing the impact to mission requirements and cost effectiveness.

Preliminary analysis was required to assess hazards and mitigation options to assure compliance with policy and guidelines. First, the background debris environment, current and projected, was needed to determine background hazard, that is, probabilities of collision for the spacecraft and components. Then an analysis of assumed spacecraft breakups was conducted to determine effects on the background and constellation members. Characterization of orbital lifetimes and re-entry for uncontrolled satellites was used to elicit collision avoidance requirements.

The results of the assessment for long-term hazards were that the effect on the background debris environment and other users of space was only significant near the planned operating altitude of the constellation; however, effects on GTO, eccentric orbits, and other sun-synchronous users requires further study. An inter-satellite collision case was not predicted, but a clearinghouse for launch window clearance and maneuver planning may be needed to support LEO operations. Given the assumptions used in the study, the hazard for satellites and components appears significant, which raises mitigation issues for limiting secondary debris; this also led to recommendations for analysis of solar panel breakup phenomena and lethality studies to develop shielding requirements for critical components.

A series of collisions were modeled, ranging from solar panel impacts (most probable) to a satellite-

satellite collision (least probable but catastrophic results highlighted importance of constellation control requirements). The area of concern for spacecraft designers and operators is collision with a debris object that would fragment the satellite, generating a debris stream potentially hazardous to other users of space, or sufficiently damage the spacecraft so that mission functionality and control are lost. The damaged satellite is then vulnerable to subsequent collisions and will not have the capability to execute post-mission disposal actions. The key result of the short-term assessment was that debris-related failures were within the tolerance for the overall planned system reliability. It was observed that break-up model improvements, hydrocode code runs and design-specific lethality studies are needed to support follow-on design activities.

Estimates were made of orbital lifetimes for uncontrolled project satellites at different times over the solar cycle throughout the mission. Decay was considered as spacecraft reaching 90 km altitude. The goal was to estimate probability of collision with a decaying satellite for the constellation members. Table 1 provides a summary assessment of the project's policy and plans compliance with NASA guidelines.

DoD Guidelines*:* Since the Phillips Laboratory serves as the technical lead for DoD space debris research, the laboratory was tasked to help develop draft guidelines for the DoD. While the NASA guidelines could be directly applicable to DoD systems, the approach to debris mitigation for DoD requires an extension of the NASA guidelines to encompass orbital testing and missile intercept testing in which debris trajectories interact with spacecraft orbits. Intercept testing also introduces missile range safety concerns for debris footprints. This includes constraining debris within range boundaries, defining keep-out zones for personnel and aircraft, and environmental effects.

To address the need for organizations participating in military space activities to mitigate the effects of space debris on their systems and the environment, the USAF Phillips Laboratory began development of debris mitigation guidelines in 1995. The NASA Handbook[16] was used to design a survey[17] to gather information on the practices of DoD systems program offices, test and evaluation agencies, range safety offices, and space system operators in determining debris effects on planned systems and tests, mitigation options, and impacts to operations. These practices included minimizing launch and operational debris, reducing risk of on-orbit explosions and collisions, utilizing space and missile test design procedures to minimize collision and environmental hazards, and employing design practices to increase system survivability with respect to space debris.

Coordination with NASA*:* In developing a joint NASA/DoD position on issues associated with the recommendations of the White House Office of Science and Technology Policy (OSTP) report, NASA

Table 1: Summary of Results

Debris Source	NASA Guideline	Project Policy/Plans
Released during Normal Operations	< 0.1 m^2-yr and < 100 obj-yr for ≥ 1 mm diameter debris	Policy of zero operational debris exceeds guidelines
Generated by Accidental Explosions	Probability of accidental explosion $P_{exp} \leq 0.0001$	Design feature (electric propulsion, no stored propellants) minimizes risk. Battery risk TBD
Collisions with Large Objects	Probability of impact with debris $\geq$ 10 cm $P_{imp} \leq 0.001$ and of damage on loss of control $P_{dam} \leq 0.001$	Operational concept of positive control for collision avoidance maneuvers and shielding of electronic boxes reduces risk
Post-Mission Disposal	3 options: decay with lifetime < 25 years; retrieve within 25 years; maneuver to perigee > 2500 km	Policy of post-mission disposal is deorbit all; with loss of propulsion, spacecraft will re-enter within 9 years.
Control of Re-entry Risk	Uncontrolled total footprint ≤ 8 m^2. Controlled re-entry no closer than 46 km from US territory	Controlled reentry to meet guideline; burnup and ground footprint TBD

P_{imp}= Probability of Impact P_{dam}= Probability of damage and DoD agreed to utilize the NASA standard as the basis for draft US Government/Industry Design Guidelines on Orbital Debris. DoD coordination on the NASA standard was requested to ensure that DoD's national security mission not be unduly constrained and that space and missile testing requirements be addressed. The NASA guidelines with any DoD revisions will be sent to the Interagency Working Group on Orbital Debris for coordination and then presented to Industry for comment at a Workshop with US Industry planned for 1997.

NASA and DoD further agreed that the strategy of approaching orbital debris mitigation through voluntary measures as outlined in the NASA Handbook and in combination with the US Government's policy of achieving technical consensus on orbital debris with the spacefaring nations is the appropriate strategy. This strategy provides adequate controls on the orbital debris environment and should be followed until such time as measurements of the environment indicate that more stringent measures are required.

3. SUMMARY

The Department of Defense space debris research program is chartered to assess the small debris environment, characterize the potential hazard to DoD assets, and to develop new mitigation techniques to further minimize the creation of debris. To meet this goal, program activities are concentrated into the areas of debris measurements, debris modeling, and debris mitigation. A phase one research program was completed in December 1993 and a phase two program began in March 1994. This paper presented several topics in the area of debris modeling, and included a brief overview of available modeling tools. Applications for these modeling capabilities include intercept test planning, on-orbit breakup event analysis, satellite design, warfare simulation, space hazards modeling, and debris mitigation studies. A Debris Analysis Workstation is being developed to meet the analysis requirements for these applications. The debris mitigation section included a discussion of the issues faced in assessing the effects of minimizing the production of debris, and included an example of a risk assessment for a proposed spacecraft system. This paper also discussed potential directions for the program to take in the future.

4. REFERENCES

1. DoD Space Policy, 4 February 1987.
2. U.S. National Space Policy, 5 January 1988.
3. "Report on Orbital Debris," Interagency Group (Space), February 1989, National Security Council, Washington D.C.
4. Maethner, S.R., A.E. Reinhardt, and L.O. Anderson, "Report on USAF Space Debris Phase One Study," Phillips Laboratory Technical Report, PL-TR--94-1042, June 1994.
5. "Orbital Debris: A Technical Assessment", The National Research Council, 1995.
6. "Interagency Report on Orbital Debris: 1995", Office of Science and Technology Policy, Washington, D.C.
7. U.S. National Space Policy, 14 September 1996.
8. Maethner, S.R., D.B. Spencer, A.B. Jenkin, "The Air Force Space Debris Research Program", AAS 95-198, February 1995.
9. Sorge, M.E., and C.G. Johnson, "Space Debris Hazard Software: Program IMPACT Version 3.0 User's Guide," Aerospace Report No. TOR-93(3076)-3, The Aerospace Corporation, El Segundo, CA, August, 1993.
10. Jenkin, A.B., "DEBRIS: A Computer Program for Debris Cloud Modeling," IAA.6.3-93-746, October 1993.
11. Mains, D.L., "DCSIM Version 1.0 User's Guide," ATM No. 94(4909-03)-1, The Aerospace Corporation, September 1994.
12. Alfano, S., and D. Negron, "Determining Satellite Close Approaches," Journal of the Astronautical Sciences, Vol. 41, No. 2, April-June 1993.
13. Chao, C.C., and M.H. Platt, "An Accurate and Efficient Tool for Orbit Lifetime Predictions," AAS 91-134, February 1991.
14. Herman D.E., "Introduction to DENSITY, a FORTRAN Program that Computes Spatial Density," ATM No. 93(3019-24)-2, The Aerospace Corporation, March 1993.
15. Spencer, D.B., et al, "The Expanding Capabilities of the Debris Analysis Workstation", SPIE 2813-12, August, 1996.
16. Loftus J.P., and R.C. Reynolds, "A Handbook to Support the NASA Policy to Limit Orbital Debris Generation" IAA.3.3-93-700, October 1993.
17. Campbell, W.S., M.E. Sorge, D.B. Spencer, and S.R. Maethner, "Proposed Development of Department of Defense (DoD) Debris Mitigation Guidelines", AAS 96-112, February 1996.